Full-Scale Experimental Validation of a DAD Post-Tensioned Concrete Connection Utilising Embedded High Force-to-Volume Lead Dampers

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ABSTRACT: An experimental validation of a jointed precast prestressed concrete connection, fitted with embedded high force-to-volume damping devices is presented. A full-scale beam-column subassembly based on Damage Avoidance Design (DAD) principles is experimentally examined to assess its seismic performance and damage avoidance capability. The test specimen is a 3D exterior connection of a jointed precast concrete frame structure, with prestress provided by unbounded post-tensioned high-alloy high-strength thread-bars.. Beam and column junctions in the joint region are armoured to avoid damage by providing steel plates at the interface surfaces. Supplemental energy dissipation is provided by high force-to-volume (HF2V) dampers internally cast into the beams adjacent to the beam-column interface. Multiple displacement histories are applied to investigate the contribution of the dampers to overall joint hysteresis and stability of the joint hysteretic performance. Tests are performed with and without the dampers connected, at a range of different post-tensioning forces, to delineate the effects of the different structural elements. Under uni-directional loading, the HF2V dampers provide significantly more damping than the post-tensioned DAD system alone. No strength degradation is observed over numerous tests and results are seen to be displacement path independent, whereby large initial cycles did not affect strength or stiffness on subsequent smaller cycles. The DAD concept is considered to be further validated based on the results of these tests.

1 INTRODUCTION

Due to cyclic loading effects, earthquakes can cause significant damage and degradation at beam-to-column connections. The development of unbonded post-tensioned concrete structural connections that provide dissipative non-linear response from gap-opening, instead of structural damage concentrated in a plastic hinge zone, has been the focus of recent research (Priestley et al. 1999; Li et al. 2008; Solberg et al. 2008). Such connections, utilising Damage Avoidance Design (DAD) principles, typically have low inherent hysteretic damping, and are therefore particularly suitable for the addition of supplemental damping systems. In prior research, this supplemental damping has typically been provided by yielding steel fuse bars (Bradley et al. 2008; Li et al. 2008). In particular, it would be more desirable to develop energy dissipation devices that consistently dissipate energy during every cycle, requiring neither maintenance nor repair following non-linear response to an earthquake.

This study presents the use of a new type of lead extrusion damper to provide supplemental damping to structural connections that follow DAD principles (Rodgers et al. 2007, 2008a). High force-to-volume (HF2V) lead extrusion dampers have several key benefits over simpler yielding steel fuse bars. Specifically, the HF2V devices can: 1) concentrate energy dissipation into the device; 2) eliminate the risk of low-cycle fatigue; 3) fit directly into the structural connection; 4) have the ability to reduce residual compression forces by creeping of the lead in the hours following a large earthquake; and 5) are economically feasible. Since neither maintenance nor repair is required following gap-opening that results in a non-linear response, the device can be mounted internally within the ends of the beams, resulting in an aesthetically pleasing solution.

Structural response for a jointed precast system is a combination of elastic member deflection and rigid body rotation. This study investigates the damper contribution to overall structural hysteretic performance, as well as the independent effects of elastic sub-assembly deformation and post-gap opening rigid-body rotation of the structural elements. Different levels of post-tensioned prestress are investigated to further delineate the contributions of elastic deflection and gap opening.

2 EXPERIMENTAL INVESTIGATION

Figure 1 presents the experimental specimen (referred to as a subassembly) used in this study. A photograph of the experimental specimen is presented in Figure 1a, along with a schematic diagram showing instrumentation in Figure 1b. The prototype 3D subassembly represents an interior joint of a ten-storey reinforced concrete building. The subassembly consisted of two beams cut at their midpoints and an orthogonal beam cut at its midpoint (the approximate location of the point of contraflexure). All beams were 560 mm deep and 400 mm wide, framing into a central 700 mm square column. The orthogonal beam is referred to as the gravity beam, and was designed for one-way precast flooring panels. The other two beams are referred to as the seismic beams, designed predominantly for seismic forces, and can be seen in Figures 1a and b.

This study investigates the contributions of unbounded post-tensioned prestress and damping forces to seismic response based on uni-directional testing of the seismic beams in the east-west direction. The longitudinal beam prestress system consisted of two concentric 26.5mm diameter high-strength, high-alloy prestressing thread-bars (MacAlloy^{TM}, UTS = 1100 MPa) passing through two 45 mm diameter PVC ducts (located 200 mm apart). The thread-bars were unbonded and post-tensioned.

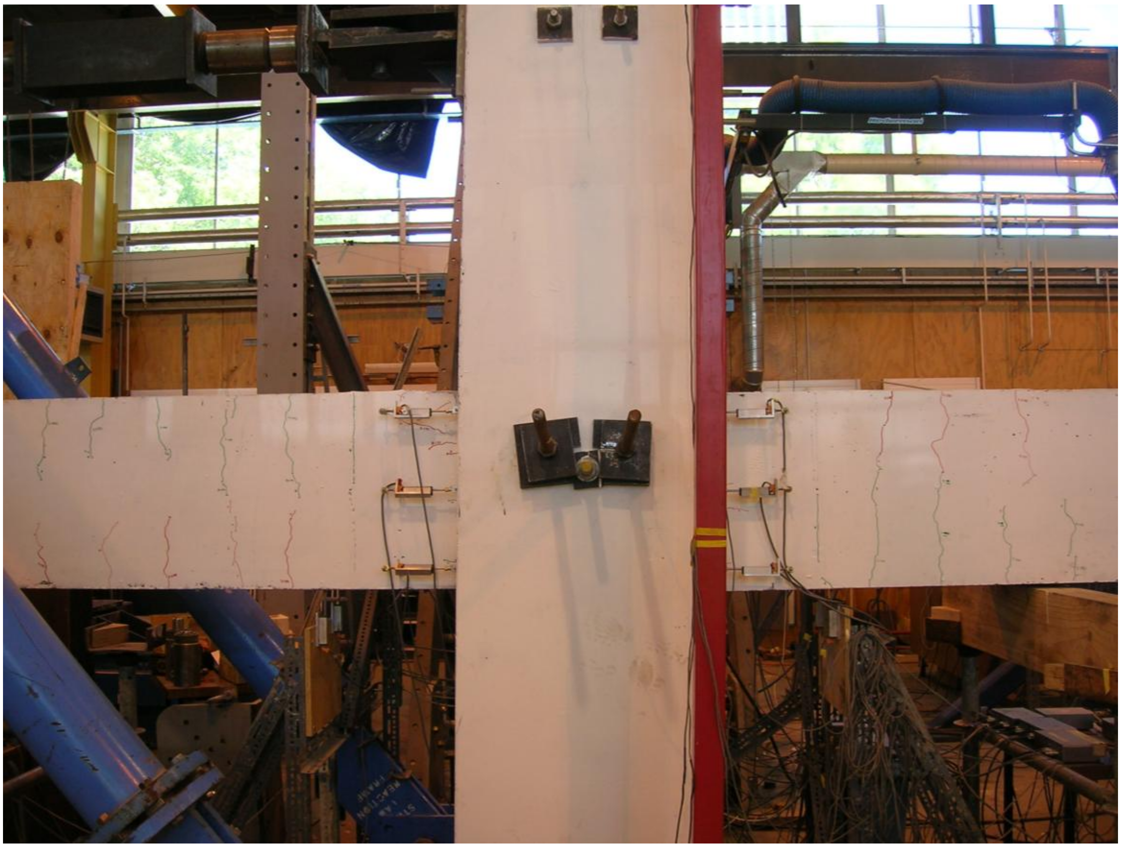
This investigation focuses on a parametric study of the subassembly at different prestress levels, with and without supplemental damping. Therefore, only uni-directional displacement profiles are reported within this paper. Full results for bi-directional testing and associated hysteretic response is presented in Solberg (2007). The subassembly was subjected to reversed sinusoidal loading at drift amplitudes up to and including 4%. To investigate the affect of large cycles on the stiffness and strength of the subassembly, tests were undertaken with both increasing and decreasing displacement amplitudes.

3 THE INTERNAL HF2V DAMPER SYSTEM AND INSTALLATION

Figure 2 presents: a) the HF2V dampers with some common items for scale; b) their performance; and c) their location in the structure. The HF2V dampers shown in Figure 2a were designed to provide supplemental damping for the joint and have a nominal design force of 250 kN. Quasi-static cyclic testing was undertaken to characterise their performance and validated the device model before placement into the beam ends. The hysteresis loops for 3 different dampers are presented in Figure 2b. The physical size and capacity of the dampers was a key consideration in the design of the structural connection.

The HF2V extrusion dampers were located in the beam end zones, in a 300 mm cast-in-situ “wet” connection as shown in Figure 2c. This cast in-situ joint design enables the dampers to be easily located and connected. The joint design also permits the beams to be adjusted for construction tolerances. The cast-in-situ ends also give designers the opportunity to place high performance concrete in the most vulnerable region of the beams near the rocking interface, for both connections with or without supplemental damping. Armouring, in the form of steel angles was located at the top and bottom of the beams. Under cyclic load reversals, the beam was designed to rock back and forth against an armour plate located on the column face. This steel-steel rocking interface inhibits any crushing of the concrete at both the beam ends and within the joint zone.

a)



b)

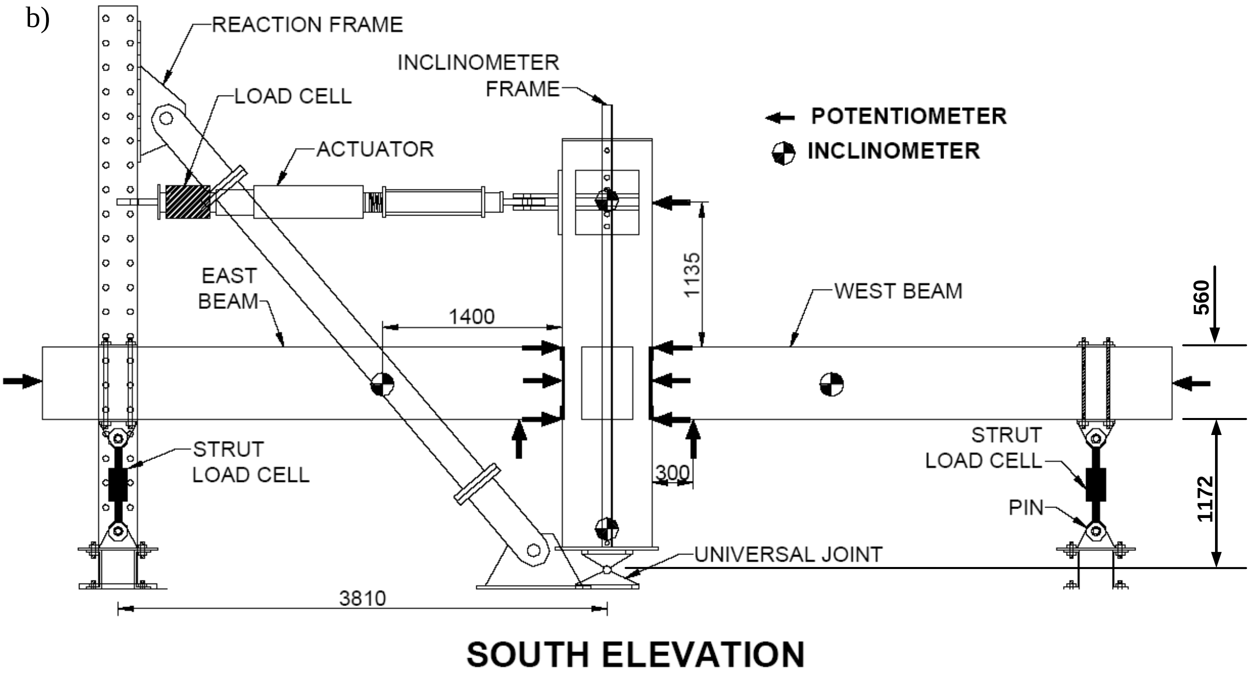
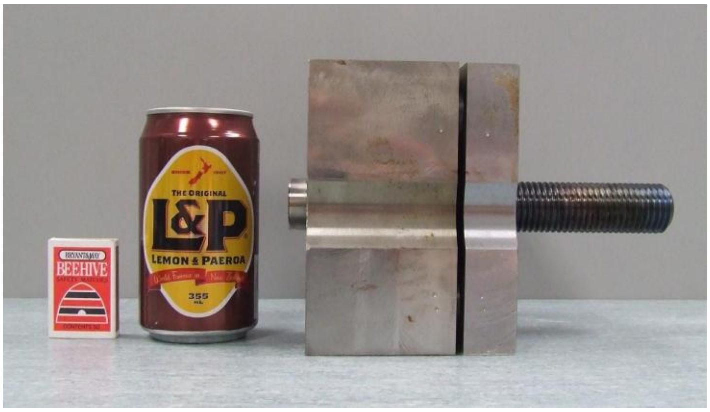
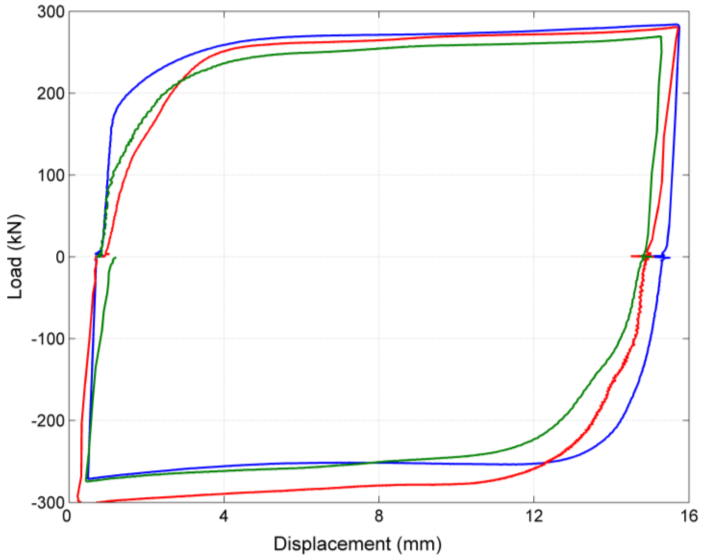


Figure 1: a) Photograph of test specimen, and b) Schematic south elevation of test setup showing dimensions (in mm) and the location of sensors.

a)



b)



c)

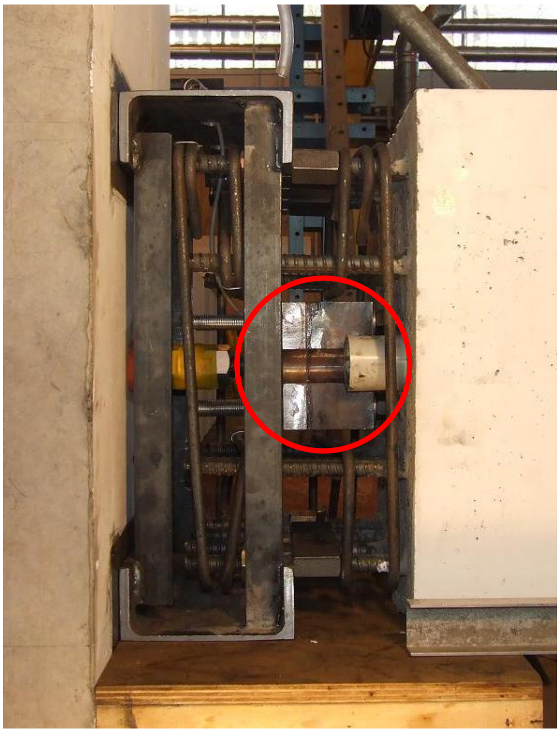


Figure 2: a) a damper with common items to indicate scale, b) hysteresis loops from direct quasi-static tests of the 3 dampers before placement into the joint, and c) a device in place in the west seismic beam awaiting the final closure pour.

4 TEST RESULTS AND DISCUSSION

The test specimen underwent quasi-static uni-directional displacement tests in the east-west direction using fully reversed sinusoidal profiles up to 4% inter-story drift. Tests were conducted under both increasing and decreasing drift amplitudes to investigate the effect of the load path. Once testing and characterisation of the specimen with the supplemental damping system was complete, the joint was opened, and the connecting rods to the dampers were cut. The specimen was then tested to characterise the overall hysteretic performance with prestress alone, without the damping system, to delineate the individual contributions.

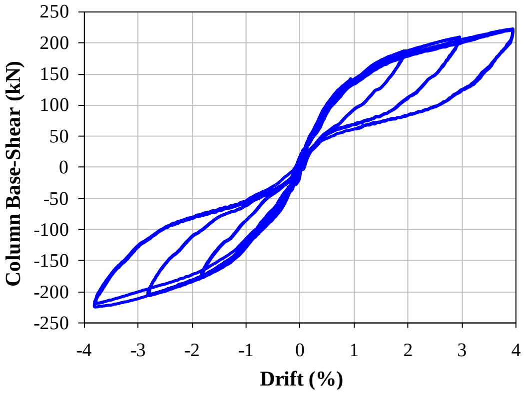
The post-tensioning system initially provided a total force to the joint of 500 kN. The experimental results for the prototype specimen at this prestress level at 1, 2, 3, and 4% drift are presented in Figure 3a. Following the application of each loading protocol, the prestress level was reduced to give total prestress forces of 400, 300, and 200 kN. The results for each of these tests at different prestress levels are presented in Figure 3 (a-d). Results are also presented for comparative purposes for the subassembly without the supplemental damping system in Figure 3 (e-h).

The reduction in initial force in the post-tensioning system was implemented to investigate the contribution of elastic member deflection to the overall hysteresis. This procedure also provided a means of experimentally investigating the reserve capacity of the joint to statically re-centre. By reducing the level of prestress for a set level of added damping, the reserve capacity for re-centering is reduced. It is evident across the results presented in Figures 3a and 3b that only a minimal reduction in column base-shear force level is seen due to the 100 kN reduction in total prestress force.

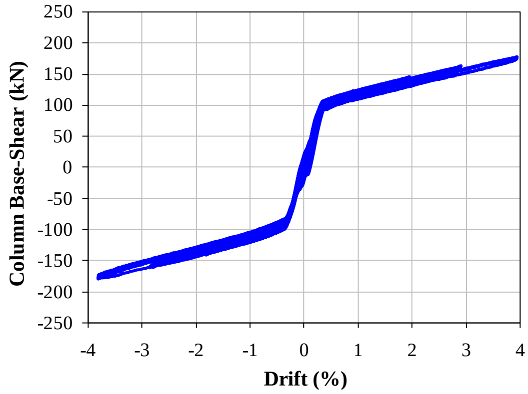
It can be seen in Figures 3 (e-h) that the overall joint hysteresis without the supplemental damping system exhibits extremely limited hysteretic energy dissipation. Previous research into jointed pre-cast concrete connections using bent tendon profiles has much larger inherent hysteretic energy due to the friction of the tendons within the ducts (Rodgers et al. 2008b). The straight tendon profile of the prototype specimen tested in this study results in much lower friction of the tendons, and as such much lower inherent damping provided by hysteretic energy absorption. Therefore, joints of this type are particularly suitable for supplemental damping systems to provide a means of absorbing energy.

It is of interest to experimentally determine the extent of prestress force reduction before the ability of the joint to statically re-centre is lost. The prestress force was successively reduced until the joint reached the static re-centring limit, at a total post-tensioning force of 200 kN. The experimental results for uni-directional displacement tests out to 4% drift and with a total prestress force of 200 kN is presented in Figures 3g and 3h. Note that at this level of post-tensioned prestress and for column drifts larger than 3%, static re-centring was only beginning to be lost, and only when the supplemental dampers were connected. It is also important to note that a total prestress force of 200 kN, represents a 60% reduction in initial prestress. The post-tensioned tendons did not yield until well beyond 5% drift and are unlikely to ever experience this level of reduction. Therefore, this result highlights the ability for designers to incorporate even larger damping forces into such a connection, for a given level of prestress. Alternatively, a designer may choose to reduce the level of initial prestress to reduce the total force being transmitted through the joint and structural elements.

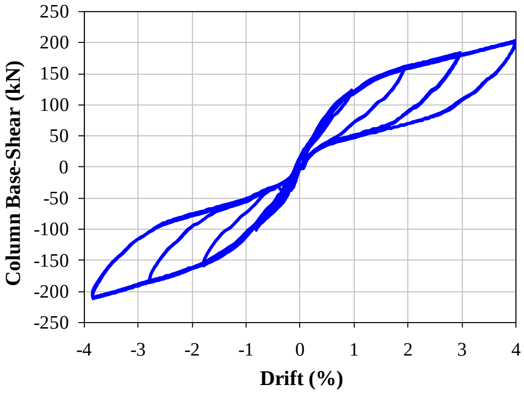
A particular feature of the DAD connections is the ability for repeated cycles to operate without stiffness of strength degradation. Figure 4 present reversed sinusoidal loading at 400 kN total prestress, for both increasing and decreasing drift amplitudes. Figure 4a presents the same hysteretic results previously presented in Figure 3b, along with the associated displacement history plotted below. Figure 4b presents results for the same joint, put through reversed displacement loading, whereby the large amplitude cycles occur first. It is evident in Figure 4 that the overall hysteretic performance was almost identical for both loading regimes, with almost no perceivable difference in the two results. This result clearly demonstrates that DAD connections can undergo repeated large drift cycles, without any stiffness of strength degradation, moreover their performance is load-path independent.



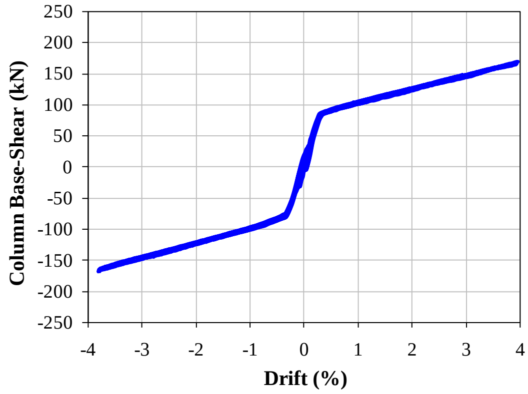
a) 500 kN total prestress, with dampers



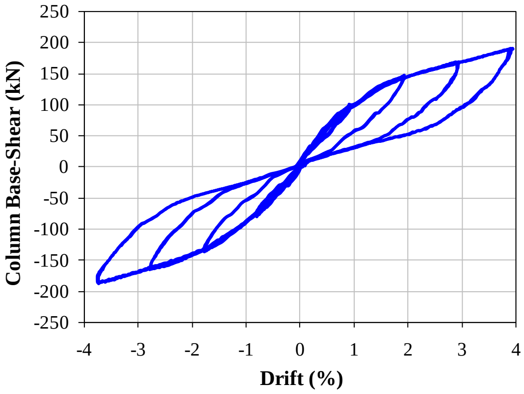
e) 500 kN total prestress, without dampers



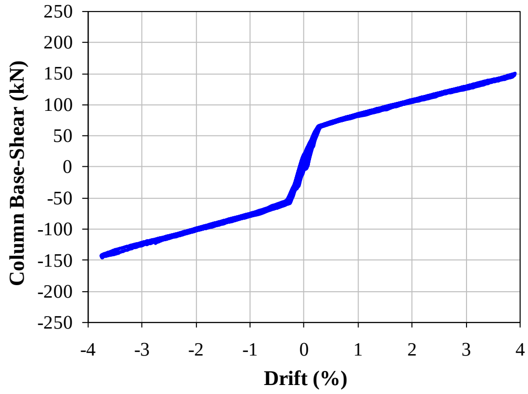
b) 400 kN total prestress, with dampers



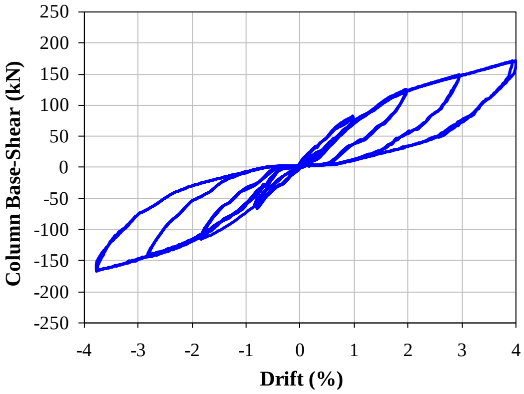
f) 400 kN total prestress, without dampers



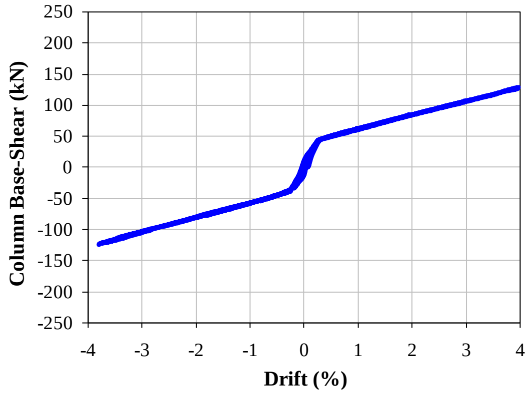
c) 300 kN total prestress, with dampers



g) 300 kN total prestress, without dampers

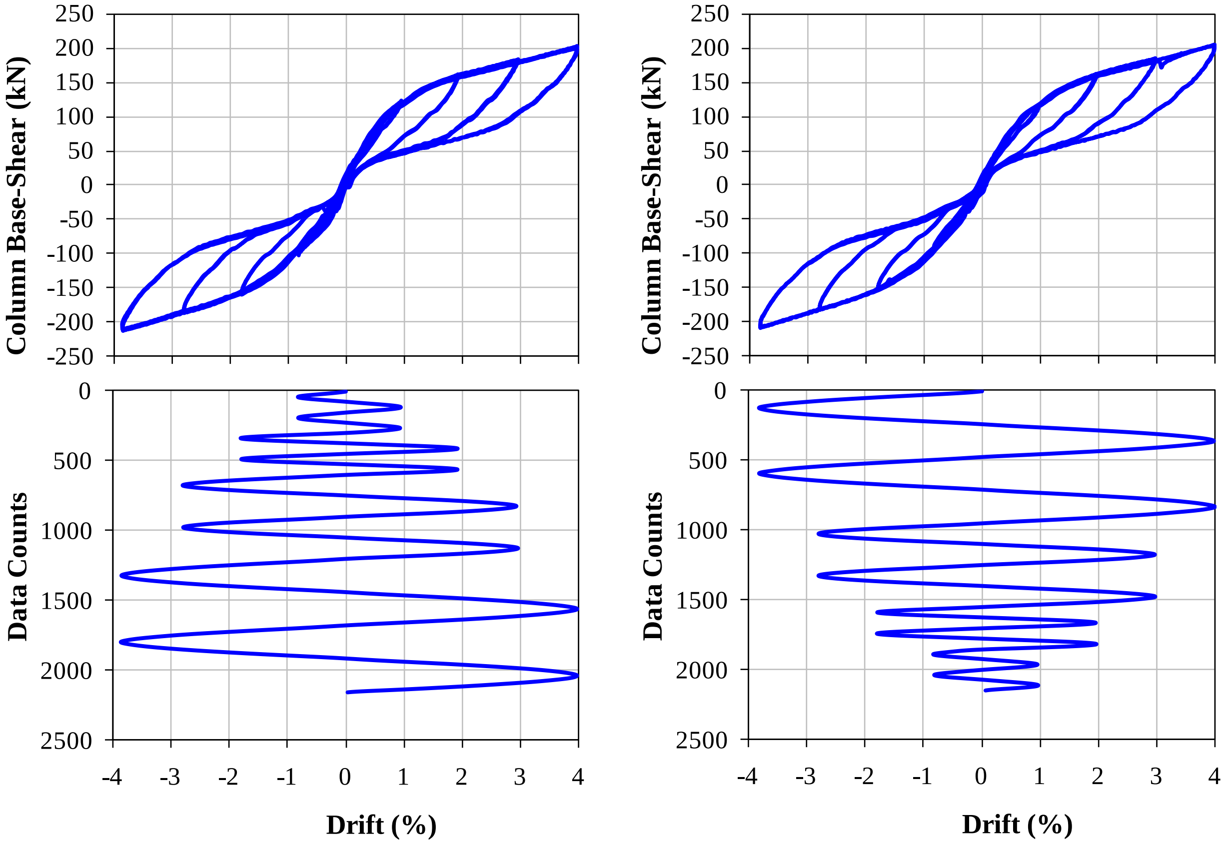


d) 200 kN total prestress, with dampers



h) 200 kN total prestress, without dampers

Figure 3: Experimental results matrix at different levels of prestress, with (a-d) and without (e-h) HF2V dampers



a) *400 kN total prestress, with dampers, increasing drift amplitude*

b) *400 kN total prestress, with dampers, decreasing drift amplitude*

Figure 4: Comparison of increasing and decreasing drift amplitudes

The ability to parametrically study a connection is unique to the Damage Avoidance Design principles, and in particular because of the inclusion of steel armouring at the rocking interface. In most other experimental test specimens, especially monolithic connections, stiffness and strength degradation prevent such an investigation. If multiple experimental specimens are constructed, then variations in material properties will affect the results, limiting the accuracy of any comparisons drawn. The use of armoured DAD connections allows repeated tests to be performed on the same experimental specimen eliminating these additional uncertainties. This adds confidence for full scale implementation.

5 CONCLUSIONS

Cyclic load test results for a full-scale post-tensioned prestressed concrete beam-to-column subassembly designed in accordance with damage avoidance principles were presented. The ability to parametrically study the joint behaviour is useful and is unique to this type of armoured DAD connection. Based on the tests conducted, the following two main conclusions are drawn:

1. The uni-directional, quasi-static testing of the subassembly has shown significant energy dissipation is provided by the supplemental damping system. Disconnection of the HF2V device resulted in negligible inherent damping for the connection. This phenomenon can be attributed to the straight tendon profile that leads to very low internal friction and consequently essentially no hysteretic energy absorption.

2. Experimental results have shown that reductions in initial prestress force level of up to 60% can be permitted without loss of overall static re-centring ability. This aspect enables designers to either increase the amount of added damping that is provided to the joint from the HF2V device, or to reduce the initial prestress level to reduce the forces transmitted through the structural elements.

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REFERENCES:

Bradley, B. A., Dhakal, R. P., Mander, J. B., and Li, L. (2008). "Experimental multi-level seismic performance assessment of 3D RC frame designed for damage avoidance." *Earthquake Engineering & Structural Dynamics*, 37(1), 1-20.

Li, L., Mander, J. B., and Dhakal, R. P. (2008). "Bi-Directional Cyclic Loading Experiment on a 3-D Beam-Column Joint Designed for Damage Avoidance." *ASCE Journal of Structural Engineering*, 134(11), 1733-1742.

Priestley, M. J. N., Sritharan, S., Conley, J. R., and Pampanin, S. (1999). "Preliminary results and conclusions from the PRESSS five-story precast concrete test building." *PCI Journal*, 44(6), 42.

Rodgers, G. W., Chase, J. G., Mander, J. B., Leach, N. C., and Denmead, C. S. (2007). "Experimental development, tradeoff analysis and design implementation of high force-to-volume damping technology." *Bulletin of the New Zealand Society for Earthquake Engineering*, 40(2), 35-48.

Rodgers, G. W., Mander, J. B., Chase, J. G., Dhakal, R. P., Leach, N. C., and Denmead, C. S. (2008a). "Spectral analysis and design approach for high force-to-volume extrusion damper-based structural energy dissipation." *Earthquake Engineering & Structural Dynamics*, 37(2), 207-223.

Rodgers, G. W., Solberg, K. M., Mander, J. B., Chase, J. G., Bradley, B. A., Dhakal, R. P., and Li, L. (2008b). "Performance of A Damage-Protected Beam-Column Subassembly Utilizing External HF2V Energy Dissipation Devices." *Earthquake Engineering & Structural Dynamics*, 37(13), 1549-1564.

Solberg, K. (2007). "Experimental and Financial Investigations into the further development of Damage Avoidance Design," Master of Engineering (ME) Thesis, University of Canterbury, Christchurch, New Zealand.

Solberg, K., Dhakal, R. P., Bradley, B., Mander, J. B., and Li, L. (2008). "Seismic performance of damage-protected beam-column joints." *ACI Structural Journal*, 105(2), 205-214.